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Research Article

Effects of TiN/CrN, CrAlN, and TiN Coatings on the Performance of AISI M2 Tool Steel

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ABSTRACT

The aim of this study is to investigate the effects of various ceramic-based coatings on the performance of AISI M2 high-speed steel punch used in the nut piercing process. AISI M2 punches were coated with TiN, TiN/CrN, and CrAlN utilizing a physical vapour deposition method. The total stroke number of the punches was used to evaluate the tool life of TiN, CrAlN, and TiN/CrN coated AISI M2 punches. AISI M2 punch coated with TiN/CrN was able to work up to greater stroke numbers than punches coated with TiN and CrAlN. Hardness and wear tests were performed to study the wear resistance of TiN/CrN and CrAlN coatings under relatively normal load conditions compared to actual working conditions (impact loading conditions) in the piercing process. The hardness and wear resistance of the CrAlN coating were greater than those of the TiN/CrN coating. The wear performance of the CrAlN coating was higher at normal loads and sliding speeds while the tool life of the TiN/CrN-coated punch was better under impact loading conditions.

Keywords: *AISI M2 tool steel, Piercing punch, TiN/CrN, CrAlN, Tool life, Nut*

TiN/CrN, CrAlN ve TiN Kaplamaların AISI M2 Takım Çeliğinin Performansına Etkileri

ÖZ

Bu çalışmanın amacı, seramik esaslı çeşitli kaplama malzemelerinin, somun delme işlemlerinde kullanılan AISI M2 yüksek hız çeliğinden üretilmiş delme zımbalarının performanslarına etkilerinin araştırılmasıdır. AISI M2 zımbalar, fiziksel buhar biriktirme tekniği kullanılarak TiN, TiN/CrN ve CrAlN ile kaplanmıştır. Takım ömrünü belirlemek için TiN, TiN/CrN ve CrAlN ile kaplanmış AISI M2 zımbaların toplam strok sayıları dikkate alınmıştır. TiN/CrN kaplı AISI M2 zımba, TiN ve CrAlN kaplı zımbalara göre daha yüksek strok sayılarına kadar çalışabilmiştir. TiN/CrN ve CrAlN kaplamaların, delme işlemindeki gerçek çalışma koşullarına (darbeli yükleme koşulları) kıyasla normal yükleme koşulları altında aşınma direncini incelemek için sertlik ve aşınma testleri yapılmıştır. CrAlN kaplamanın sertlik ve aşınma direnci TiN/CrN kaplamadan daha yüksek olmuştur. Normal yükleme koşulları ve kayma hızlarında, CrAlN kaplamanın aşınma performansı daha yüksek iken darbeli yükleme koşullarında, TiN/CrN kaplama, takım ömrünün daha yüksek olmasını sağlamıştır.

Anahtar Kelimeler: *AISI M2 takım çeliği, Delme zımbası, TiN/CrN, CrAlN, Takım ömrü, Somun*

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I. INTRODUCTION

Fasteners, such as nuts and bolts, are preferred and employed in most applications due to their ease of installation and disassembly and low cost [1,2].

Fastener manufacturers place a high value on the efficiency of the forming processes used to produce parts such as nuts and bolts. The quality of a fastener part is influenced by various factors, including forming tools, materials, and forming processes. In cold forming processes, tools are subjected to high impact loads at high forming rates. This impact causes the tool to deteriorate over time and eventually become unusable. Tool damage can result in tool replacement as well as production halting, machine modification for new tools, and discarding of some of these manufactured parts [3]. For instance, Raja and Sornakumar [4] reported that a machine capable of producing 155 nuts per minute while constructing nut holes could only manufacture 137 nuts per minute due to frequent punches failure, and that the cost of forming punches accounted for 30% of the overall cost of one nut. For this reason, in order for the punches to have a long tool life, they have to be made of materials with high strength, improved wear resistance, high toughness, and low friction coefficient.

Forming tools, such as punches, are generally made of high-speed tool steels, such as AISI M2, to enable high strength against impact loads. Punching tools should be resistant to wear in addition to being high strength and tough enough to prevent it from breaking under impact loading conditions [5,6]. If the punch surface contacting the formed part wears and the amount of wear rises, the hole diameter of the part may alter and become dimensionally unstable, as well as the surface of the hole being of poor quality, which may result in higher manufacturing costs. Surface quality (performance) of forming tools, such as enhanced wear resistance, can be improved by utilizing various surface treatments [7-11]: plasma vapour deposition (PVD), chemical vapour deposition (CVD), plasma immersion ion implantation, and plasma electrolyte nitriding.

Various surface coatings, such as TiN, CrN, TiAlN, CrAlN, and diamond-like carbon (DLC), can be used on steel-based tools. Dubar et al. coated AISI M2 tool steel with TiN using PVD and CVD, and reported that the steel tool coated with TiN using CVD had a longer lifetime and lower friction coefficient than that of the steel tool coated via PVD [12]. Brizuela et al. studied the tribological properties of CrN and CrAlN coatings applied to an AISI M2 steel disc [13]. CrAlN coated AISI M2 steel showed superior tribological properties than CrN coated AISI M2 steel, with a lower friction coefficient; also, CrAlN coating had stronger thermal stability than CrN coating. Yousefi et al. coated AISI M2 steel with TiN, CrCN, and DLC utilizing PVD, plasma-enhanced chemical vapour deposition (PECVD), and thermo-reactive deposition (TRD) processes [14]. They stated that DLC had lower roughness, which indicates the surface quality of a coating, than TiN and CrCN coatings, however, TiN had higher hardness and a longer lifetime than CrCN and DLC. Spain et al. applied TiN, CrN, TiAlN, and CrAlN coatings on AISI M2 tool steel using electron beam plasma-assisted physical vapour deposition (EBPAPVD) process [15]. They reported that CrAlN and TiAlN coatings had higher hardness than TiN and CrN coatings and that CrAlN coated tools had a 2-3 lifetime advantage over the other coatings.

In terms of the performance of coatings on tool steels, multi-layered coatings, such as TiN/CrN and CrN/CrAlN, may outperform single (mono) layered coatings [16]. Barshilia et al. compared the hardness of multi-nanolayered CrN/CrAlN coating to the hardness of mono-layered CrN and CrAlN coatings and reported that multi-nanolayered CrN/CrAlN coating was harder than mono-layered CrN and CrAlN coatings [17]. Another study compared the tribological properties of mono-layered TiN and CrN coatings deposited on M2 tool steel using the PVD process to those of multi-layered TiN/CrN coatings [18]. Although mono-layered TiN coating had the highest hardness value, the best wear resistance was achieved for multi-layered TiN/CrN coating. As a result, the main advantage of multi-layered coatings is that their properties outperform the properties of the individual coating layers that comprise them.

Most studies have investigated the performance of coatings on AISI M2 steel under relatively normal loading conditions; however, studies on the performance of coated AISI M2 steel under actual working conditions (impact loading conditions) have been very limited. The performances (tool life) of TiN, CrAlN, and TiN/CrN coated AISI M2 steel piercing punches working under impact loading were evaluated in this study. Under relatively normal loading conditions, the wear resistance of TiN and TiN/CrN coatings was also analysed.

II. MATERIALS, METHODS, AND EXPERIMENTAL DESIGN

A. MATERIALS AND METHODS

AISI M2 high speed steel was utilized as a substrate material for the piercing punch used in nut manufacturing. Using the physical vapour deposition (PVD) process, three types of coatings (mono-layered TiN and CrAlN and multi-layered TiN/CrN) were deposited on AISI M2 steel. Figure 1 depicts specimens of uncoated and coated AISI M2 piercing punches. A technical drawing showing the dimensions of a coated piercing punch is illustrated in Figure 2.

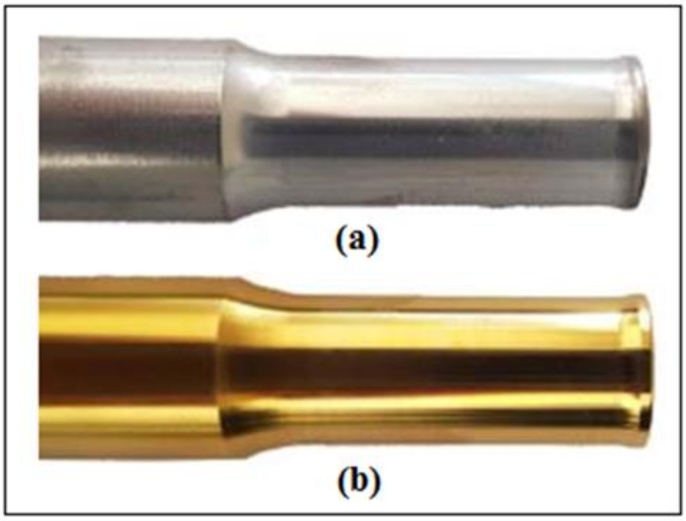

Figure 1. ***(a)*** *uncoated and* ***(b)*** *coated AISI M2 piercing punches*

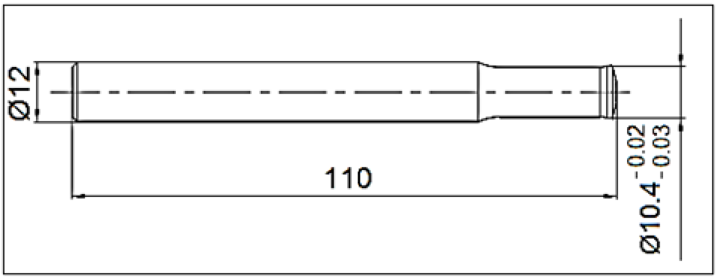

Figure 2. *Technical drawing of a coated piercing punch*

The following are the main stages of nut production: shearing, forging, piercing, and tapping. The piercing process is generally performed at the end of the cold forming process of a nut. At that stage, the piercing punch attached to the moving part of the die system pushes the nut toward the piercing sleeve. After the nut rests on the piercing sleeve, the piercing punch continues to move until the scrap is separated completely from the nut. In this study, the nut piercing process had a stroke speed of 90 rpm. Figure 3 shows the piercing process and a pierced nut.

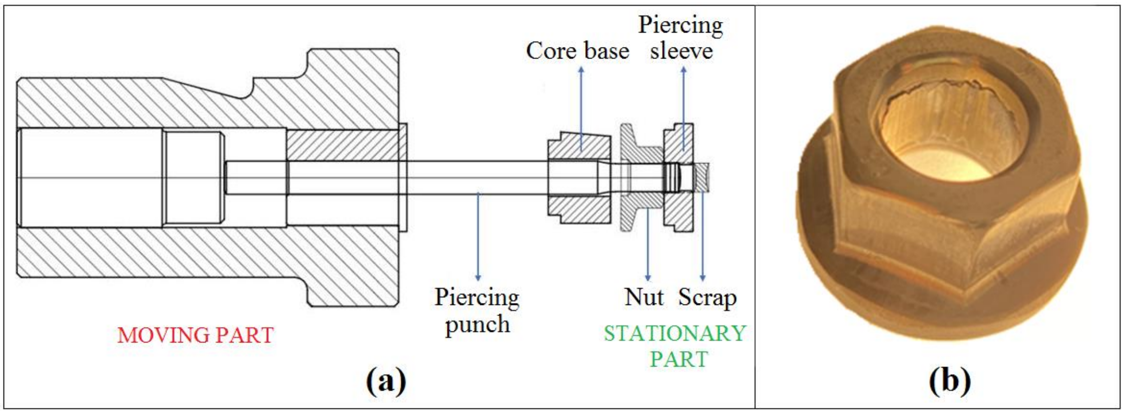

Figure 3. (a) *Piercing process and* ***(b)*** *a pierced nut*

The tool life of TiN, CrAlN, and TiN/CrN coated AISI M2 piercing punches was determined by stroke number and was considered as the total number of pierced nuts at which the coated punch rendered the nut ineffective.

The Vickers hardness tester was used to measure the hardness of coatings under a load of 245.2 mN (25 gf).

A ball-on-disc wear test was used to measure the wear resistance of mono-layered CrAlN and multi-layered TiN/CrN (Figure 4). Wear tests (ball-on-disc, CSM-Tribometer) were performed at loads of 2, 5, and 8 N, sliding speeds of 0.05, 0.10, and 0.15 m/s, and a distance of 500 m under dry sliding conditions in the air with a relative humidity of about 50%RH and at room temperature of (~25 °C). In the wear test, a WC-Co ball with a diameter of 6 mm was used.

Optical images of the worn surfaces of the TiN, CrAlN, and TiN/CrN coated-punches subjected to actual working conditions in the piercing process in the manufacturing of nuts the manufacturing of nuts were taken to examine the relationship between tool life and wear of the piercing punches.

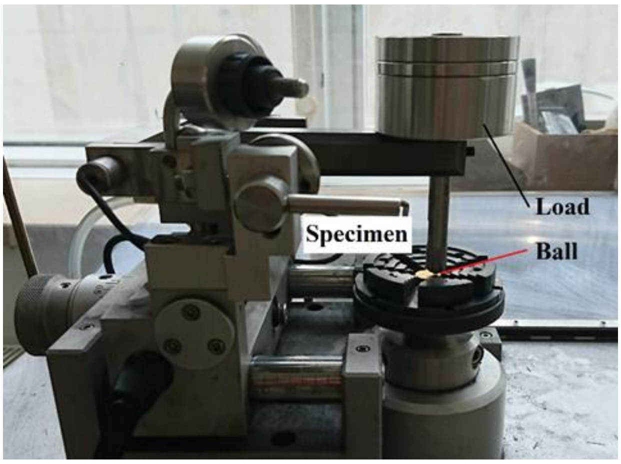

Figure 4. *Ball-on-disc wear testing machine*

B. EXPERIMENTAL DESIGN

A full factorial design was used to design the experiments for the wear test of TiN and CrN coatings. The experimental run was randomized in order to minimise the error introduced by the experimental process [19]. The experiment using the middle (centre, mean) values of the parameters is replicated more than once in the experimental design for statistical analysis to estimate the experimental error

[20]. For this purpose, the combination of middle load and sliding speed values of 5 N and 0.10 m/s were replicated five times as illustrated in Section III.B.

The experimental results for the wear tests of CrAlN and TiN/CrN coatings were analysed, and the results of the analysis of variance (ANOVA) were performed using the Design Expert software. This software was also used to analyse the influence of load and sliding speed on the wear rate of CrAlN and TiN/CrN coatings.

III. RESULTS AND DISCUSSION

A. TOOL LIFES OF TiN, CrAlN, AND TiN/CrN COATED AISI M2 STEEL PUNCHES

Hardness of mono-layered TiN and CrAlN and multi-layered TiN/CrN coated AISI M2 piercing punches are shown in Figure 5. The hardness of the CrAlN coating was higher than that of the other two coatings.

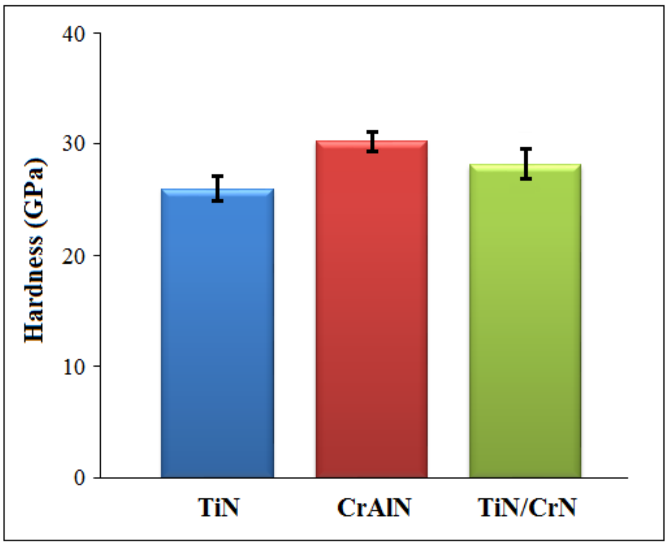

Figure 5. *Hardness of TiN, CrAlN, and TiN/CrN coated AISI M2 steel punches*

The amount of wear on a tool is one of the most influential factors in determining its life [21]. When surface roughness and/or geometric accuracy of the last produced product reach levels (values) that make it useless, the tool may likewise reach the end of its useful life. In this study, the tool life of TiN, CrAlN, and TiN/CrN-coated AISI M2 piercing punches was determined by stroke number and was considered as the total number of pierced nuts at which the coated punch rendered the nut ineffective. As seen in Table 1, when the TiN/CrN-coated AISI M2 punch was used, a higher number of nuts could be pierced than with the TiN and CrAlN coatings. The total number of pierced nuts increased by 88.9% and 42.6%, respectively, when TiN/TiC coatings were used instead of TiN and CrAlN coatings.

Table 1. *Tool (punch) life and reduction (%) in diameter of the coated punch*

Coating material	**Tool (Punch) life (Strok number / Number of pierced nuts)**	**Diameter of the last pierced nut** *(mm)*	**Reduction in diameter of punch** *(%)*
TiN	188333±16499	10.28	1.15
CrAlN	249501±13199	10.35	0.48
TiN/CrN	355760±26398	10.18	2.11

On the other hand, the amount of reduction in the diameter of the punch was kept at a lower level in the production with the CrAlN-coated punch, which could indicate that the CrAlN-coated punch was worn less than the other two coatings. All wear-loss equations derived from various types of wear mechanisms indicate a strong link between hardness and wear resistance [22-24]. For this reason, the fact that the diameter of the CrAlN-coated punch was kept at a lower level compared to the TiN and TiN/CrN coatings can be attributed to the higher hardness of CrAlN coating.

Considering Figure 5 and Table 1, it is interesting to note that, despite the fact that the hardness of the CrAlN coating was higher, the total number of nuts pierced with this punch was less than that of the TiN/CrN-coated punch, indicating that its tool life was shorter. It can be explained by the following reasons. First of all, it can be stated that the load between the punch and the nut during the nut piercing process can be characterized as an impact load. Impact load may cause material fatigue, resulting in subsurface crack nucleation and subsequent delamination of surface material [25]. Delamination wear occurs at a particular depth from the surface of the worn part due to the presence of maximum shear stress and triaxial compressive stress state at this depth [27]. This causes cracks to expand, propagate, and interact with adjacent cracks over time. Cracks tend to propagate parallel to the surface, resulting in the delamination of flake-like sheets (layers) from the surface. For all these reasons, although CrAlN-coated punch had higher hardness, the total number of nuts pierced using this punch was lower than that of the TiN/CrN-coated punch. The regions shown in Figure 6(b) may have formed on the punch surface as a result of delamination.

The TiN/CrN-coated punch had a greater reduction in diameter than the CrAlN-coated punch (Table 1), implying that the TiN/CrN-coated punch experienced more wear. However, the total number of nuts pierced by the TiN/CrN-coated punch (tool life of this punch) was more than that of the CrAlN coated punch, as aforementioned. This can be attributed to inhibiting or retarding delamination wear in the TiN/CrN coating because the probability of delamination wear in multi-layered coatings under impact load is lower than in mono-layered coatings for the following reason. Interfaces in a multi-layered coating that act as crack movement barriers, resulting in delamination wear retardation and inhibiting [18]. While delamination wear formed on the surface of the CrAlN-coated punch (Figure 6(b)), abrasive wear was the primary wear mechanism at the TiN- and TiN/CrN-coated punches, as illustrated in Figure 6(a) and (c). The abrasive wear grooves formed on the TiN-coated punch were deeper, wider and more deformed than those formed on the TiN/CrN-coated punch, indicating that the TiN-coated punch had more wear.

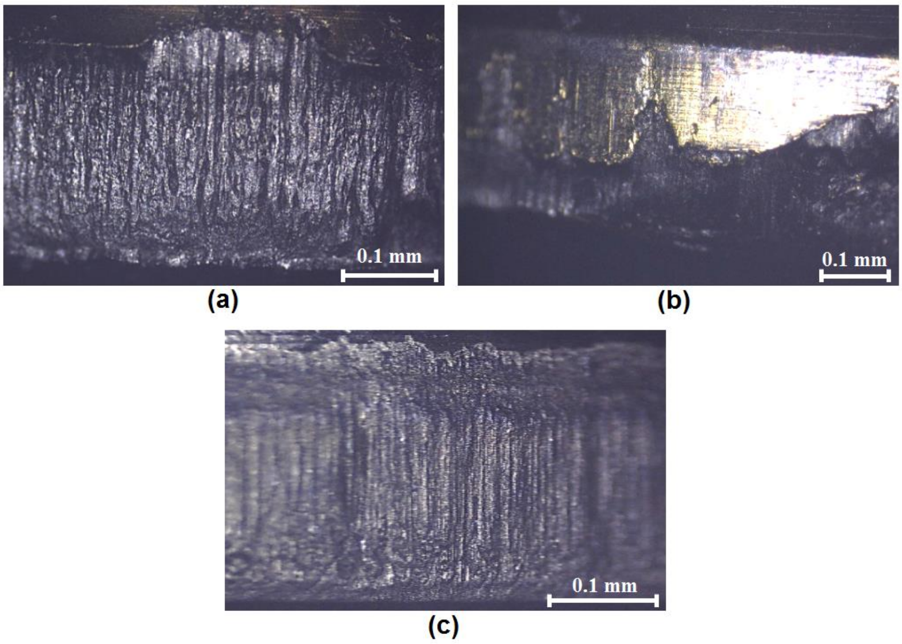

Figure 6. *Worn surfaces of* ***(a)*** *TiN,* ***(b)*** *CrAlN, and* ***(c)*** *TiN/CrN-coated piercing punches*

It should be noted once more that the TiN-coated punch had the lowest tool life and hardness when compared to the CrAlN and TiN/CrN-coated punches, and that because the load was applied in the form of impact during nut production, the CrAlN-coated punch had a shorter tool life despite having a higher hardness than the TiN/CrN-coated punch. However, because the CrAlN coating has a higher hardness than TiN/CrN coating, its wear behaviour may differ when subjected to non-impact (relatively normal) loading. For this purpose, the wear behaviours of CrAlN and TiN/CrN coatings were also studied in this study at various loads and sliding speeds under non-impact conditions, as will be discussed in the following section.

B. ANALYSIS OF WEAR RATES OF CrAlN AND TiN/CrN COATINGS

The experimental design, run order of the experiments, parameters, and the experimental results (wear rate) are shown in Tables 2 and 3.

Table 2. *Experimental design, parameters and their values, and results of wear tests of CrAlN coating*

Std. order	**Run order**	**Coating material**	**Load** *(N)*	**Sliding speed** *(m/s)*	**Wear rate** *[(mm³/N·m)·10⁻⁸]*
1	6	CrAlN	2	0.05	15.1
2	3	CrAlN	5	0.05	18.3
3	1	CrAlN	8	0.05	23.2
4	5	CrAlN	2	0.10	18.4
5	8	CrAlN	5	0.10	21.2
6	11	CrAlN	8	0.10	28.9
7	4	CrAlN	2	0.15	22.7
8	2	CrAlN	5	0.15	27.4
9	10	CrAlN	8	0.15	38.5
10	9	CrAlN	5	0.10	20.9
11	13	CrAlN	5	0.10	21.0
12	7	CrAlN	5	0.10	21.4
13	12	CrAlN	5	0.10	20.7

Table 3. *Experimental design, parameters and their values, and results of wear tests of TiN/CrN coating*

Std. order	**Run order**	**Coating material**	**Load** *(N)*	**Sliding speed** *(m/s)*	**Wear rate** *[(mm³/N·m)·10⁻⁸]*
1	3	TiN/CrN	2	0.05	15.9
2	8	TiN/CrN	5	0.05	19.7
3	12	TiN/CrN	8	0.05	26.5
4	10	TiN/CrN	2	0.10	18.7
5	4	TiN/CrN	5	0.10	24.0
6	11	TiN/CrN	8	0.10	34.6
7	1	TiN/CrN	2	0.15	23.1
8	2	TiN/CrN	5	0.15	32.5
9	9	TiN/CrN	8	0.15	45.0
10	7	TiN/CrN	5	0.10	23.8
11	13	TiN/CrN	5	0.10	22.7
12	6	TiN/CrN	5	0.10	23.4
13	5	TiN/CrN	5	0.10	22.9

Table 4. *Analysis of variance (ANOVA) of experimental design for CrAlN coating*

Source	Sum of squares	Degrees of freedom	Mean square	F value	p-value
Model	416.51	5	83.3	189.96	< 0.0001
Load	197.23	1	197.23	449.75	< 0.0001
Sliding speed	170.67	1	170.67	389.18	< 0.0001
Load*Sliding speed	14.82	1	14.82	33.8	0.0007
Load*Load	14.96	1	14.96	34.12	0.0006
Sliding speed*Sliding speed	6.44	1	6.44	14.7	0.0064
Residual	3.07	7	0.44		
Lack of Fit	2.78	3	0.93	12.68	0.0164
Pure Error	0.29	4	0.073		
Cor Total	419.58	12			
R^2	0.9927				

Table 5. *Analysis of variance (ANOVA) of experimental design for TiN/CrN coating*

Source	Sum of squares	Degrees of freedom	Mean square	F value	p-value
Model	711.44	5	142.29	289.36	< 0.0001
Load	390.43	1	390.43	793.99	< 0.0001
Sliding speed	247.04	1	247.04	502.39	< 0.0001
Load*Sliding speed	31.92	1	31.92	64.92	< 0.0001
Load*Load	16.42	1	16.42	33.38	0.0007
Sliding speed*Sliding speed	9.84	1	9.84	20.02	0.0029
Residual	3.44	7	0.49		
Lack of Fit	2.19	3	0.73	2.33	0.2156
Pure Error	1.25	4	0.31		
Cor Total	714.88	12			
R^2	0.9952				

Analysis of Variance (ANOVA) was performed on the wear test results obtained from the CrAlN and TiN/CrN-coated AISI M2 specimens in order to validate the reliability of the experimental wear tests and to show the effects of wear load and sliding speed on the wear rate, as illustrated in Tables 4 and 5. R^2 values of CrAlN and TiN/CrN were 0.9927 and 0.9952, respectively. This implies that the statistical model could explain 99.27% and 99.52% of the variability in the response (wear rate), respectively. P-value in ANOVA reveals whether the model factors are significant. If this value is less than 0.05, the factors are considered significant. P-values for load, sliding speed, their interaction (load*sliding speed) and quadratic effects (load*load and sliding speed*sliding speed) in ANOVA of CrAlN and TiN/CrN were less than 0.05, indicating that the load and sliding speed, their interaction quadratic effects were significant on the wear rate of CrAlN and TiN/CrN coatings.

The effect of each factor on the response can be determined in statistical analyses by dividing the squares of each factor by the total sum of squares of the model. Using the data in Tables 4 and 5, the effects (%) of load and sliding speed on the wear rate of CrAlN and TiN/CrN coatings were calculated in this study. The load and sliding speed had a much greater influence on the wear rate; however, the influences of their interaction (load*sliding speed) and quadratic effect (load*load and sliding speed*sliding speed) were fairly minor (Figures 7 and 8). The load had the greatest influence on the wear rate of CrAlN and TiN/CrN, by 49% and 56%, respectively, and it should also be noted that it had a stronger influence on the wear rate of TiN/CrN than all of the other factors, as seen in Figures 7 and 8.

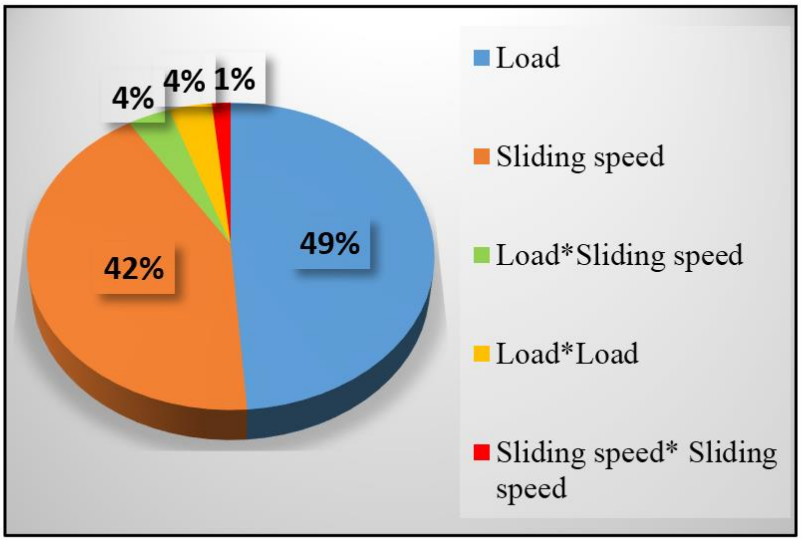

Figure 7. *Effects (%) of load, sliding speed, and their interaction and quadratic effect on the wear rate of CrAlN coating*

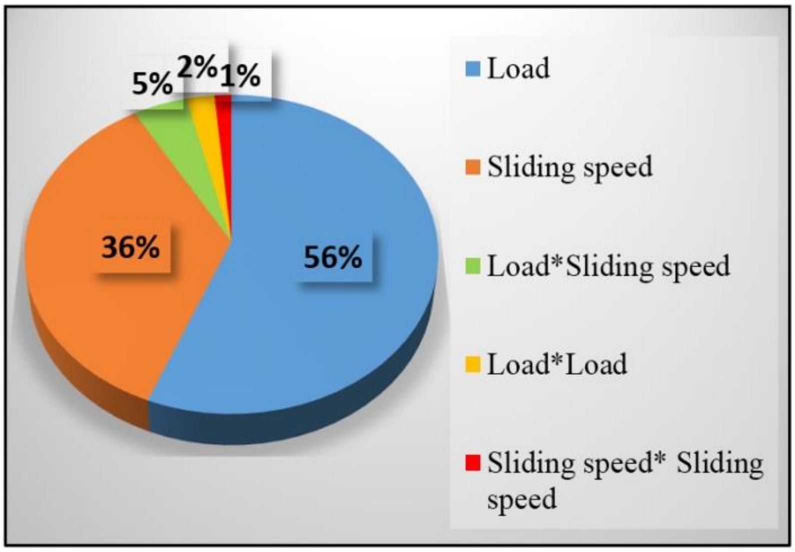

Figure 8. *Effects (%) of load, sliding speed, and their interaction and quadratic effect on the wear rate of TiN/CrN coating*

Figures 9 and 10 illustrate 2D and 3D response surface plots of the wear rate of CrAlN and TiC/CrN coatings as a function of load and sliding speed. At a given load, the wear rate of CrAlN and TiC/CrN coatings increased with increasing sliding speed. Similarly, as the load rose, the wear rate of CrAlN and TiC/CrN coatings increased at a certain sliding speed. The increase in wear rate with an increase in load at relatively lower sliding speeds was less than the rise in wear rate with an increment at relatively higher sliding speeds.

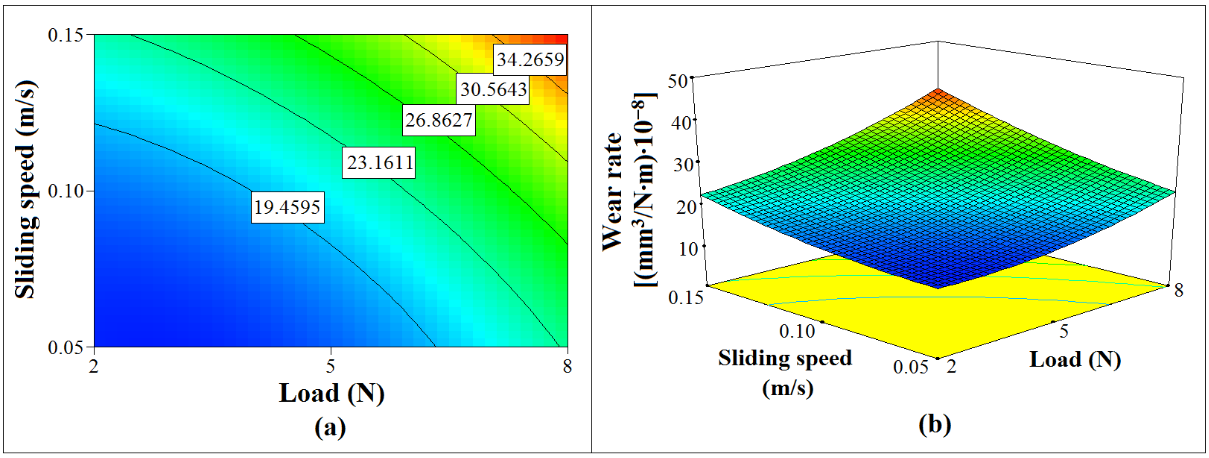

Figure 9. (a) *2D contour and* ***(b)*** *3D response surface plots of the effects of load and sliding speed on the wear rate of CrAlN coating*

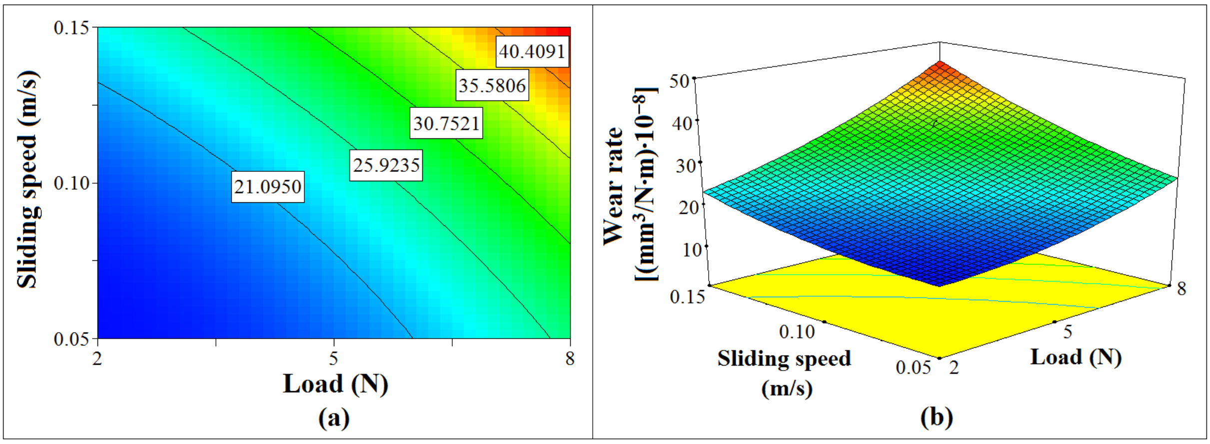

Figure 10. (a) *2D contour and* ***(b)*** *3D response surface plots of the effects of load and sliding speed on the wear rate of TiN/CrN coating*

As shown in Figure 11, with a sliding speed of 0.05 m/s and a load increase from 2 N to 8 N, the wear rates of CrAlN and TiN/CrN increased by 53.6% and 66.7%, respectively. However, at a sliding speed of 0.15 m/s, as the load increased from 2 N to 8 N, the wear rate of CrAlN and TiN/CrN increased by 69.6% and 94.8%, respectively.

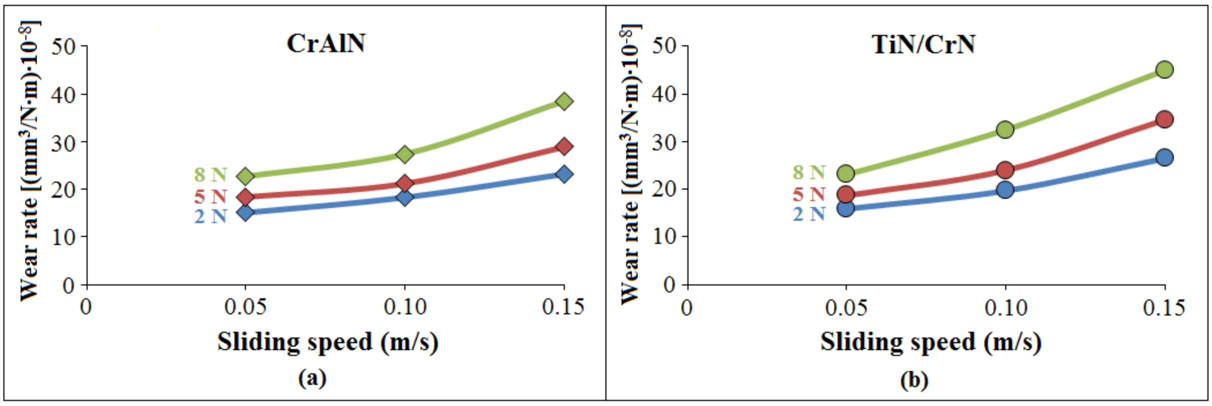

Figure 11. *Wear rates of* ***(a)*** *CrAlN and* ***(b)*** *TiN/CrN coatings at various loads and sliding speeds*

When the wear rates of CrAlN and TiN/CrN coatings were compared, it was inferred from Figures 9-11, that the wear resistance of the CrAlN coating was greater than that of the TiN/CrN coating. This can be attributed to the following reasons. The first reason could be that, as seen in Figure 5, the hardness of the CrAlN coating was higher than that of the TiN/CrN coating, which may have resulted in greater wear resistance (lower wear rate) for CrAlN. The second reason can be related to regime of coefficient of friction (COF) of the coatings during the wear test. The regime of COF of coatings may be separated into three stages in this study based on assessment processes of COF as a function of sliding distance: initial, transition, and steady stages. The initial stage corresponded to a shorter sliding distance and lower COF values [28]. The transition stage occurred between the initial and steady stages, and COF rose from a low value to a relatively higher one during this stage. The steady stage was defined as the point at which COF values stabilized.

The COF of CrAlN coating was higher than that of TiN/CrN coating at both the initial and transition stages of the wear test (Figures 12 and 13). During the deposition process, macroparticles can be generated on and in Al-containing coatings [29], which could be one of the causes for the higher COF of the CrAlN coating. During the transition stage, the force required to deform and fracture the asperities primarily contributed to the friction force; therefore, because CrAlN coating has a higher hardness, a higher frictional force occurs in the CrAlN coating [28,30,31], which could have resulted in a higher COF of the CrAlN coating compared to the TiN/CrN coating. The transition stage became shorter as the load and sliding speed increased. It can be attributed to the higher load easily and rapidly deforming the asperities [31]. It is also possible that the asperities could easily be deformed as a result of the softening impact of temperature rise caused by high sliding speed. The COF of TiN/CrN coating showed fluctuating trend throughout both the transition and steady stages, as shown in Figure 12. This could be due to the COF of TiN and CrN layers differing from one another. Because each TiN and CrN layer in the multi-layered TiN/CrN coating was nanometre thick, layers with different properties were encountered as the wear surface during wear, which might have resulted in fluctuating COF in the TiN/CrN coatings. This could be one of the reasons for the increased wear rate in the TiC/CrN coating.

The third factor influencing the wear rate of the ceramic coatings can be associated with the wear debris removal efficiency. During the wear of CrAlN coating and TiN and CrN layer in TiN/CrN coating, wear debris such as Cr_2O_3, Al_2O_3, and TiO_2 can form [32]. As stated in the literature [28], wear debris removal efficiency in CrAlN coating is better than in CrN coating, which could be one of the reasons CrAlN coating had a higher wear resistance in this study. Another factor that can affect the wear rate is the temperature oxidation resistance of the coating. The temperature rises during wear testing due to friction between contacting materials (parts), and this is especially noticeable at high load and sliding speed, which can lead to tribological oxidation of coatings [30]. As stated in the literature, non-oxidized layers is more lubricous [32]. This could imply that reducing the quantity of oxidation will lessen the wear rate. AlCrN coating has more high temperature oxidation resistance than CrN coating [30]. As a result of this, the higher oxidation resistance of CrAlN coating may have contributed to its lower COF and higher wear resistance (lower wear rate) in this study.

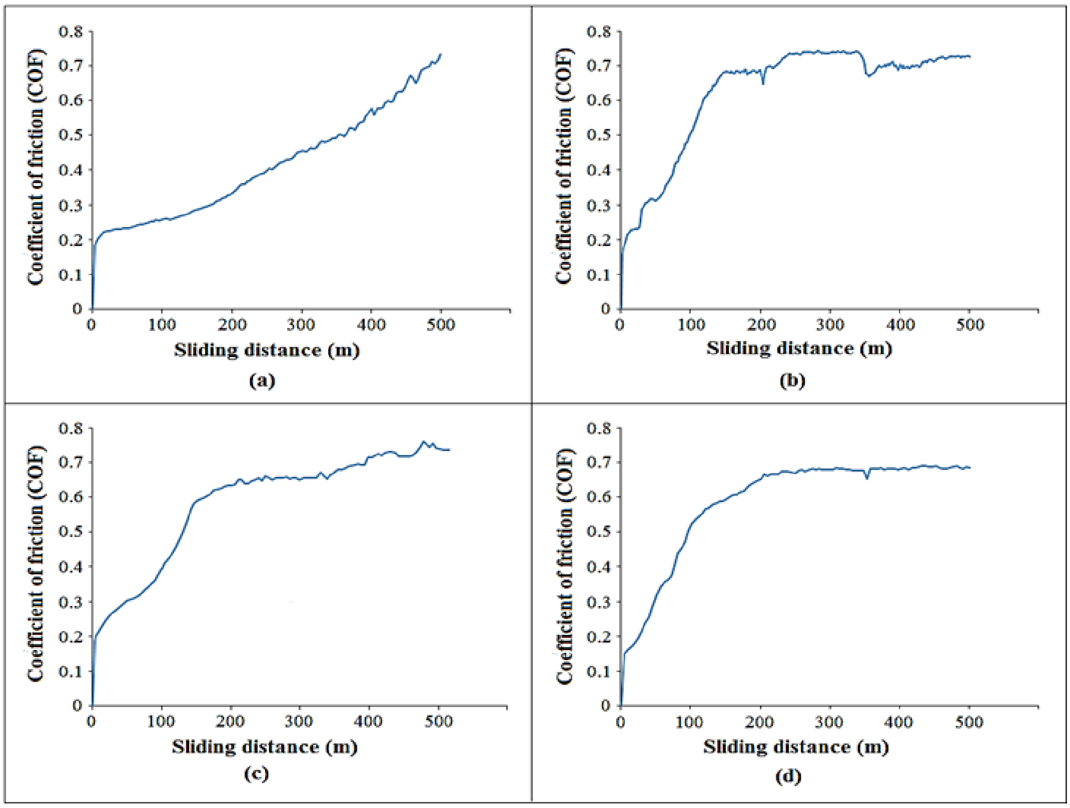

Figure 12. *Coefficient of friction (COF) of TiN/CrN coating at various loads and sliding speeds* ***(a)*** *2N, 0.05 m/s,* ***(b)*** *2N, 0.15 m/s,* ***(c)*** *8N, 0.05 m/s, and* ***(d)*** *8N, 0.15 m/s*

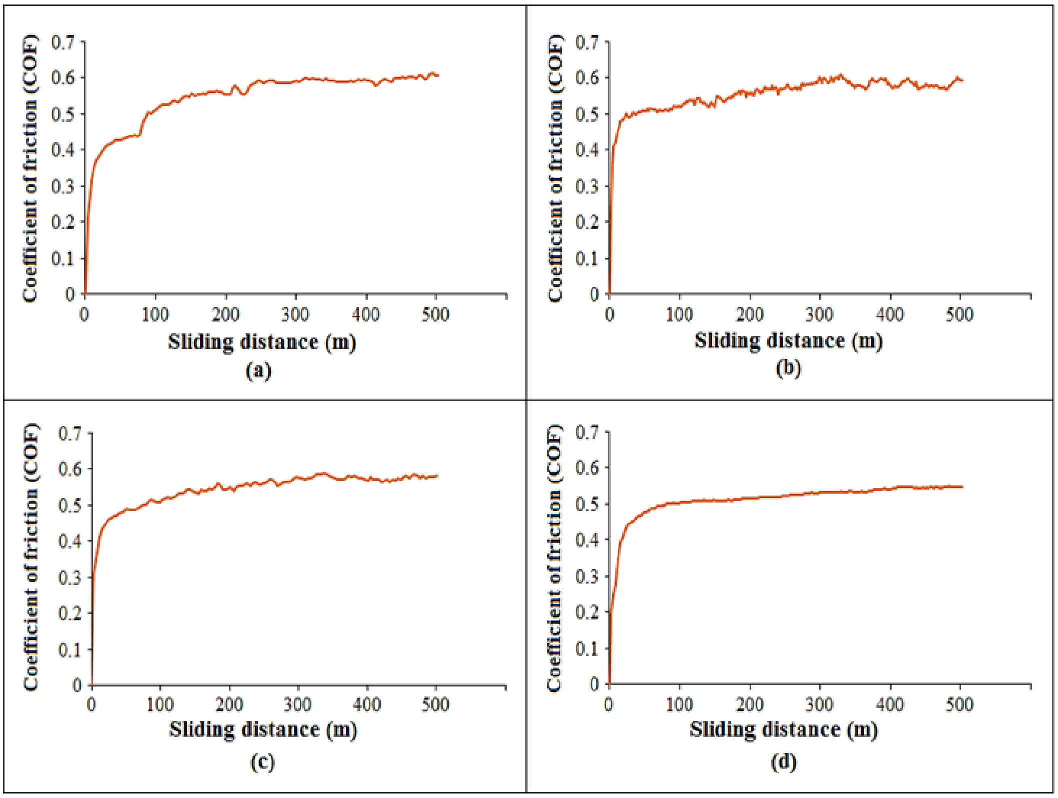

Figure 13. *Coefficient of friction (COF) of CrAlN coating at various loads and sliding speeds* ***(a)*** *2N, 0.05 m/s,* ***(b)*** *2N, 0.15 m/s,* ***(c)*** *8N, 0.05 m/s, and* ***(d)*** *8N, 0.15 m/s*

IV. CONCLUSIONS

The performances (tool life) of TiN, CrAlN, and TiN/CrN-coated AISI M2 piercing punches in the manufacturing of nut were studied, and also hardness and wear tests were carried out to analyse the wear resistance of TiN/CrN and CrAlN coatings under relatively normal load conditions compared to actual working conditions (impact loading conditions) in the punching process. The findings were listed below:

- The tool life of the TiN/CrN-coated AISI M2 piercing punch was 88.9% and 42.6% more than that of TiN and CrAlN-coated punches, respectively.
- Although the diameter of the CrAlN-coated punch was reduced less in the manufacturing of the nut and its hardness was higher, its performance was inferior to TiN/CrN coating when the loading was in the form of impact (piercing action in the production of nut); on the other hand, under normal load conditions, the CrAlN coating had better wear performance than the TiN/CrN coating.
- Load and sliding speed had a considerable impact on the wear performance of CrAlN and TiN/CrN coatings, while their interaction had a negligible. Load had a greater influence on wear rate than sliding speed. The wear rate of the CrAlN and TiN/CrN coatings increased with increasing load and sliding speed, with the rise in wear rate being greater at relatively high load and sliding speed.
- The coefficient of friction (COF) of CrAlN coating was higher than that of TiN/CrN coating during the initial and transition stages of the wear test. The COF of TiN/CrN fluctuated during the wear test, which might have contributed to the greater wear rate of the TiN/CrN coating.

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